



The Future of Astrometric Catalogs

Kenneth J. Johnston
Scientific Director
U.S. Naval Observatory
6 Dec 2000



DOD DATA/USERS

ALMANACS

CATALOGS

Software Support

Floppy

Air

Missile Support

Anti-Satellite

Test Range Support

Astronomical

Nautical

**Special Tables
Moonrise etc.**

Anti-Missile Systems

Positioning

Space Surveillance

All DoD Components
• STELLA
• SLAP
• NAVSSI

• All Ships, Submarines and Aircraft
• Ground Forces
• Shore Activities (R&D)
• Spacecraft
• NIMA

• CBM (USAF)
• Trident (USN)

• BMDO (Kinetic & Directed Energy)
• ARPA

• ASAT

• NIMA
• INS

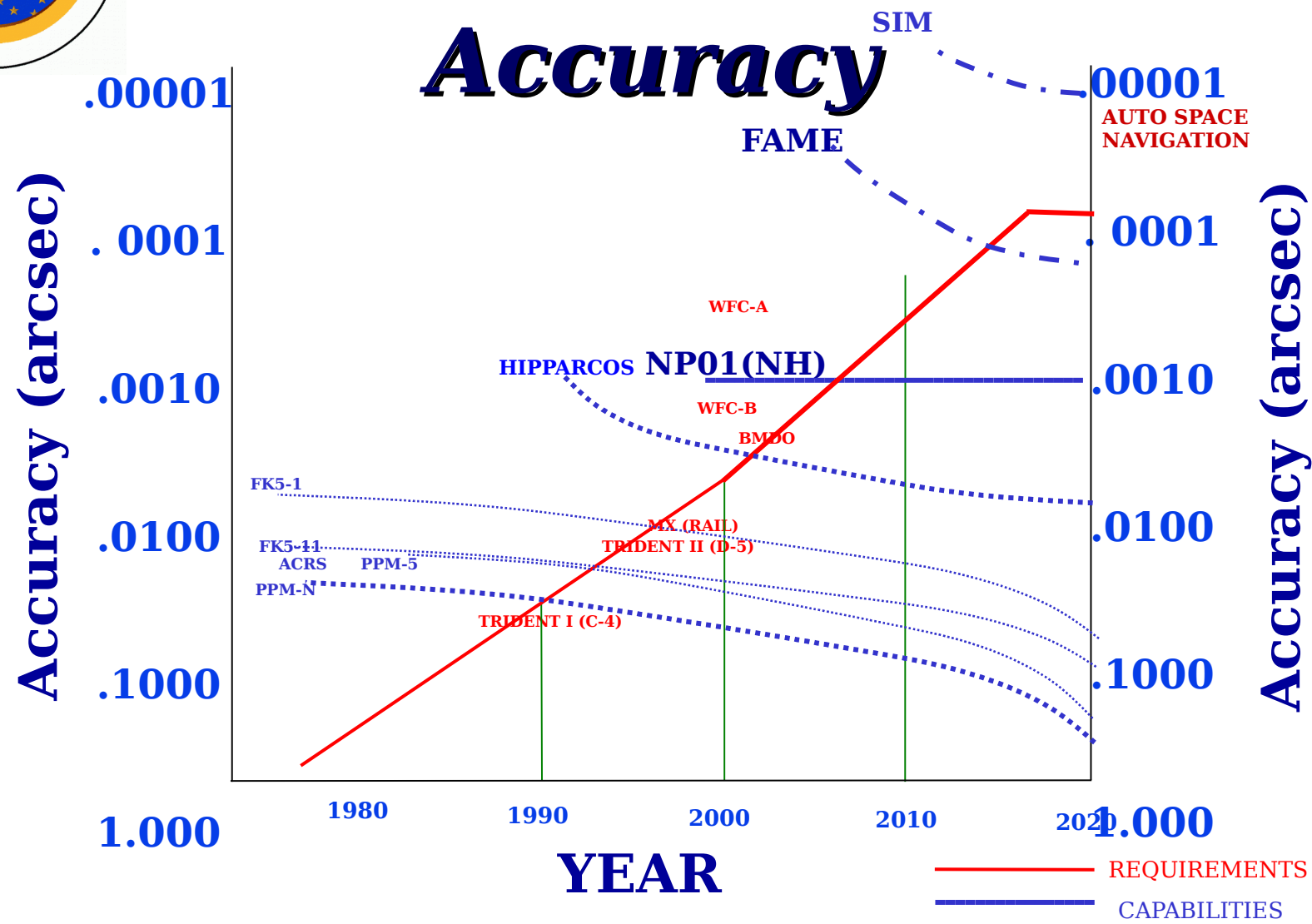
• East Test Range
• Holoman AFB
• NAWC
• NUMC

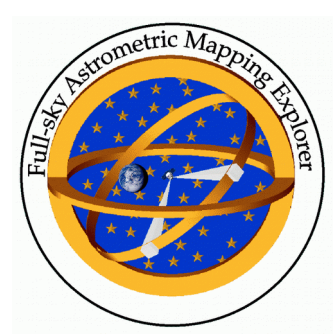
• Laser Clearing House
• NAVSPASUR
• USAF Optical Tracking
• SPACECOM

DOD USERS



Requirements & Star Position Accuracy





Ground Systems

- ◆ **Precise Astrometric Accuracy**
 - **Navy Prototype Interferometer**
 - **Keck Interferometer**

- ◆ **Surveys**
 - **UCAC**
 - **Sloan Digital Sky Survey**
 - **2Mass**



NPOI Arial View

KECK INTERFEROMETER





Space Missions

- ◆ Hipparcos
- ◆ Full-sky Astrometric Mapping Explorer (FAME)
- ◆ Space Interferometer Mission (SIM)
- ◆ Global Astrometric Interferometer for Astrophysics (GAIA)



Mission Description

◆ Survey Missions

- FAME 40 million stars to $m_V=15$, accuracy at $m_V=9$ is 50 μas
- GAIA 1 billion stars to $m_V=20$, accuracy at $m_V=15$ is 10 μas

◆ Pointed Missions

- SIM 10,000 selected stars with an accuracy of 4 μas at $m_V=12$. Can integrate on stars to give this accuracy at $m_V=20$.



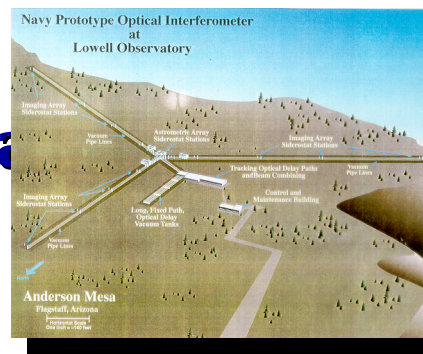
Capabilities of Astrometric Space Missions

Mission	Agency	Launch	No. of Stars	Mag Limit	Accuracy (mas)	Accuracy (mag)
Hipparcos	ESA	1989	120000	12	1	10
DIVA	Germany	2003	40 million	15	0.2 5	9 15
FAME	USNO/ NASA	2004	40 million	15	0.050 0.300	9 15
SIM	NASA	2007	10000	20	0.003	20
GAIA	ESA	2009	1 billion	20	0.003 0.010 0.200	12 15 20



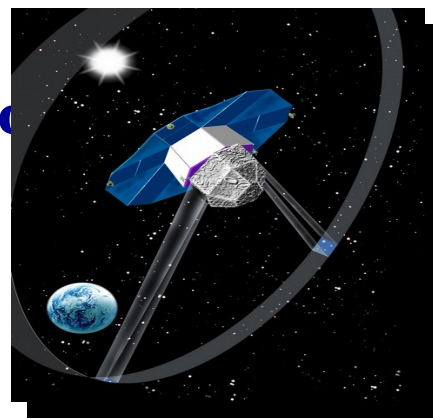
Missions: *Launch Date*

2000—Navy Prototype Optical Interferometer



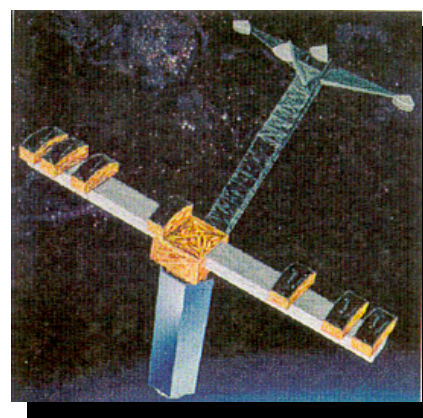
~ **1.0 mas**

2003—FAME
★ Full sky Astrometric Mapping Explorer



~ **0.05 mas**

2008—SIM
★ Space Interferometry Mission



~ **0.004 mas**

2012—GAIA
★ Global Astrometric Interferometer

~ **0.010 mas**



High Accuracy Astrometry DoD Relevance (1 of 2)

- ◆ **Precise inertial reference frame**
 - **Astrometry and reference frame maintenance are Navy (USNO) mission**
 - **Astrometric requirements currently met by Hipparcos astrometric satellite data 1991.25**
 - ▶ **Degrades with time due to proper motion inaccuracies**
 - ▶ **In 2010 current requirements no longer met**
- ◆ **FAME provides 0.000050 arcsecond precision for short term needs**
- ◆ **FAME provides 0.00010 arcsecond precision over long term to meet current and future needs**



High Accuracy Astrometry DoD Relevance (2 of 2)

- ◆ **Develop optical interferometry in space**
 - **FAME serves as pathfinder for Optical Interferometry (OI) in space**
 - ▶ **Characterize materials and techniques for OI**
 - ▶ **Precursor for NASA, future NASA astrometry missions (SIM, TPF)**
 - ▶ **Precursor for space based imaging missions**
 - **Develop technology for inertial orientation and navigation using only stellar data**
 - ▶ **Precursor for future high precision star trackers**
 - ▶ **Navigation by stars only, 1.0m precision in space**
- ◆ **Fundamental astronomy and astrophysics**
 - **Stellar distances, parallaxes, proper motions**
 - **Planetary information**
 - **Galactic structure, rotation, cosmic distance scale**



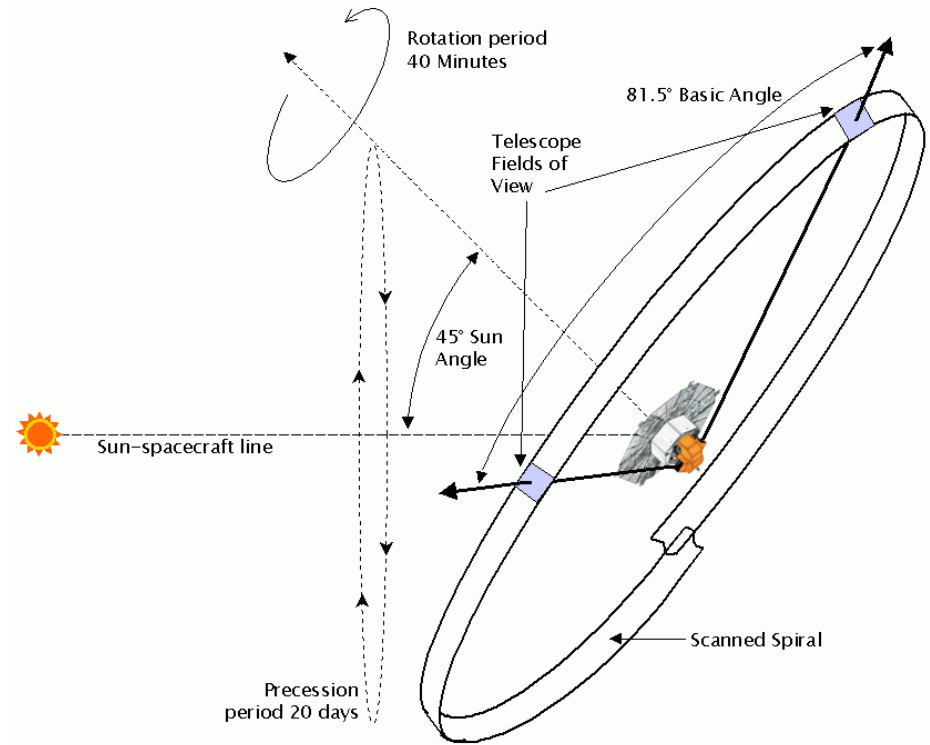
Technical Goals and Objectives of FAME

- ◆ **FAME will perform an all sky, astrometric survey with unprecedented accuracy**
 - **Upgrades existing star catalogs by providing a precision catalog of 4×10^7 Stars**
 - **Provides positions of bright stars ($5 < m_v < 9$) to $< 50 \mu\text{as}$**
 - **Provides positions of fainter stars ($9 < m_v < 15$) to $< 500 \mu\text{as}$**
 - **5 year extended mission allows for accurate measurement of stellar parallax, proper motions, and monitoring of stellar variability**
 - **Photometric data in four Sloan DSS bands (g' , r' , i' , z')**



FAME Mission Description

- ◆ **The telescope has two fields-of-view separated by a 81.5° basic angle**
- ◆ **The spacecraft will rotate with a 40 minute period with the apertures sweeping out a great circle on the sky**
- ◆ **The spacecraft rotation axis is at a 45° angle to the Sun**
- ◆ **The solar radiation pressure on the solar shield results in precession about the Sun-spacecraft line with a 20 day period**
- ◆ **The spacecraft is in Geosynchronous orbit for continuous contact**

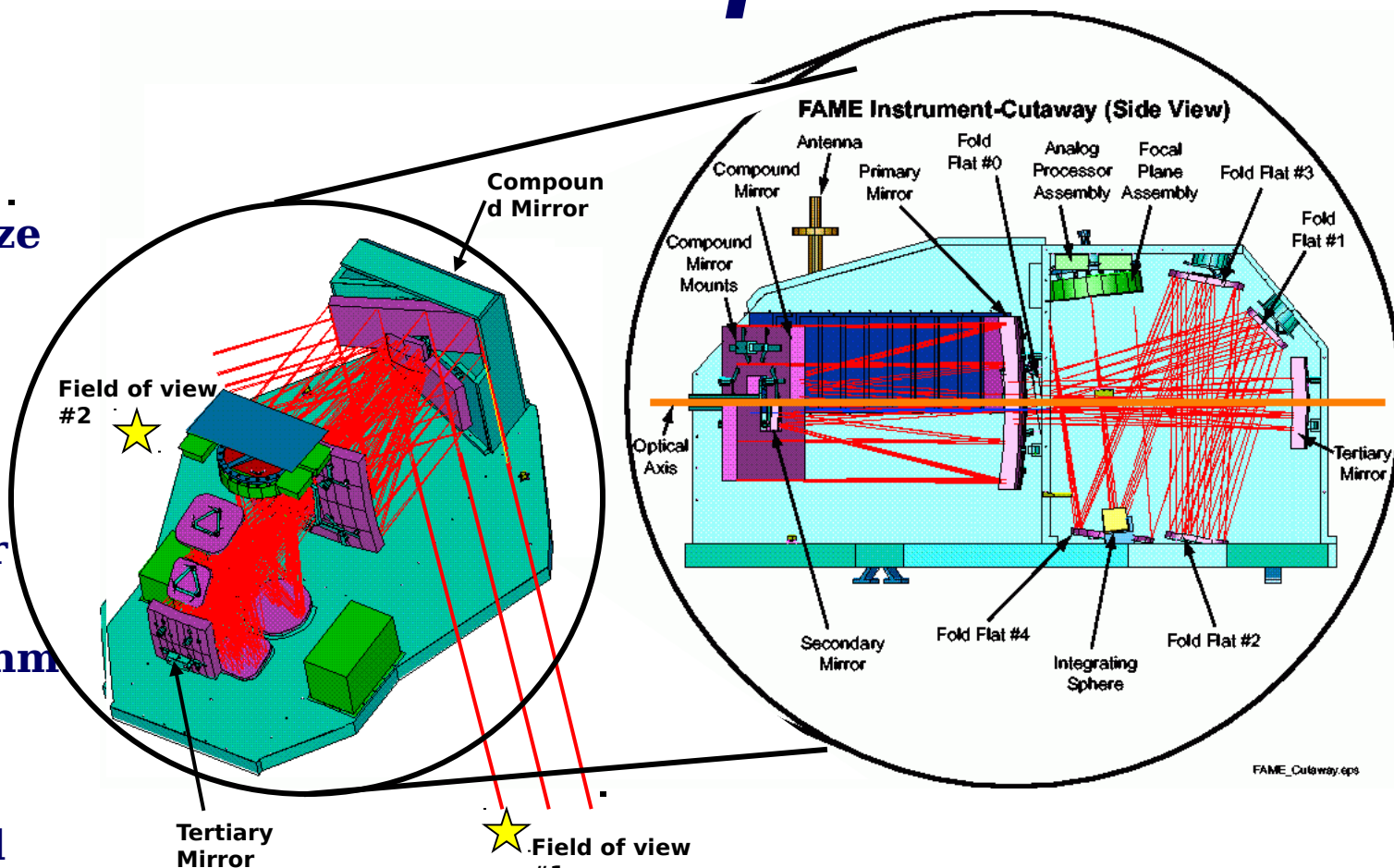


The FAME observing concept - The axis of the FAME spacecraft is pointed 45° from the Sun and precesses around the Sun with a 20 day period. The FAME spacecraft rotates with a 40 minute period. The two fields of view are normal to the rotation axis and are separated by a 81.5° degree basic angle.



FAME Instrument Description

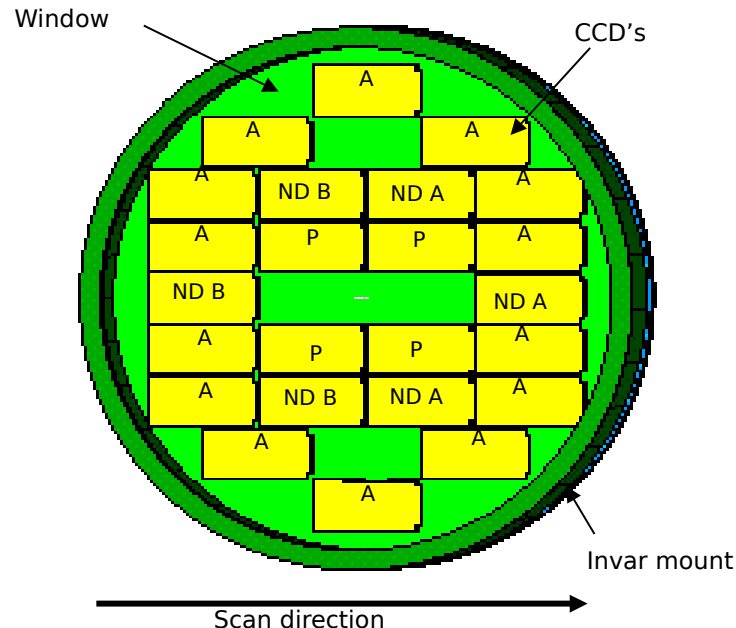
- ◆ **Two input apertures**
- ◆ **60 × 25 cm aperture size (each)**
- ◆ **Total mass 229 kg**
- ◆ **Total power 272 W**
- ◆ **400 to 900nm spectral range**
- ◆ **Back illuminated CCDs**



- ◆ **Instrument developed by Lockheed Martin Missiles and Space ATC**



FAME Instrument Description



The FAME focal plane - 24 2k · 4k CCDs arranged around a 1.1° diameter field of view. Devices marked with 'P' are the 4 photometric CCDs and devices marked with 'A' are the 20 astrometric CCDs. The 6 devices marked with 'ND' have neutral density filters for astrometry of brighter stars.

- ◆ **Telescope produces images of Stars using 24 large format CCDs**
 - **Images of stars are continually traversing CCD array as the spacecraft rotates**
 - **CCDs use time delay integration**
 - **Synchronization of CCD clock rate and image motion is assured via rotation rate sensors**
 - **Star images are time tagged, windowed, and transmitted to Earth.**
 - **6 CCDs are covered by neutral density filters for astrometry of bright stars**



Fame Error Sources

- ◆ **CCD characteristics**
 - ▶ Read noise, QE variation, etc.
- ◆ **Instrument alignment**
 - ▶ PSF variations
- ◆ **Instrument stability**
 - ▶ Thermal effects
- ◆ **Spacecraft**
 - ▶ Knowledge of spacecraft velocity
- ◆ **Stellar/external**
 - ▶ Photon statistics



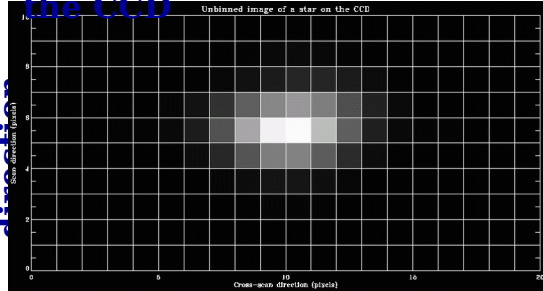
FAME Estimated Error Budget

Error Source	Error (μas) a priori	Error (μas) a posteriori
Photon Statistics		
$m_V=9$	540	540
$m_V=15$	10800	10800
Read Noise ($7e^-$ rms, $m_V=9$)	6600	6600
QE Variation	560	<10
λ-dependent absorption in CCD	300	30
Charge transfer effects	800	80
Incorrect Stellar Spectrum	4000	50
Model		
Undetected Companions	60	60
Onboard clock error	<100	<1
Telescope geometry variations	100	<10
Optical Distortion	2000	20
Refraction in CCD window	1	<1
Rotation Rate Changes	10^6	25
Ephemeris (1cm/sec knowledge)	7	<1

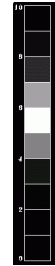
On-board data processing

On-chip binning

Unbinned image of a star on the CCD



scan direction
n

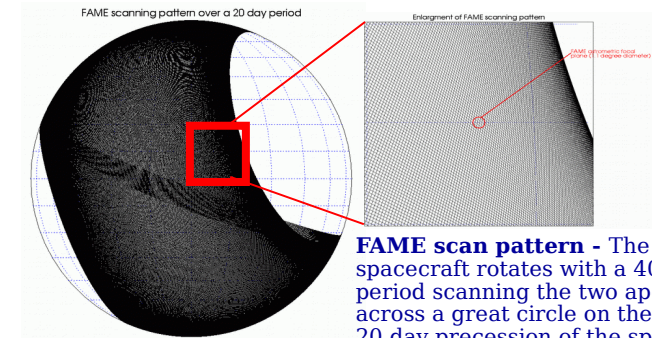


scan direction
n

Pixels in the cross-scan direction

- ★ The data from most stars are binned by 20 in the cross-scan direction on the CCD before being read-out

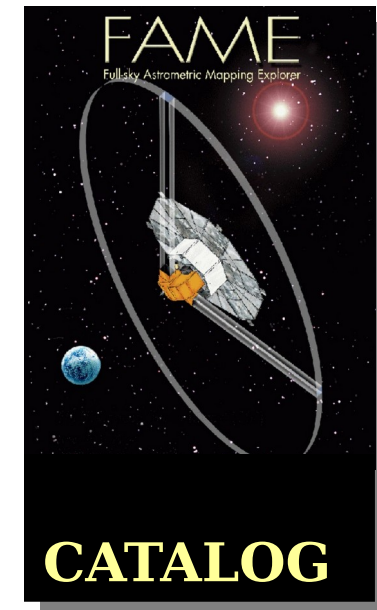
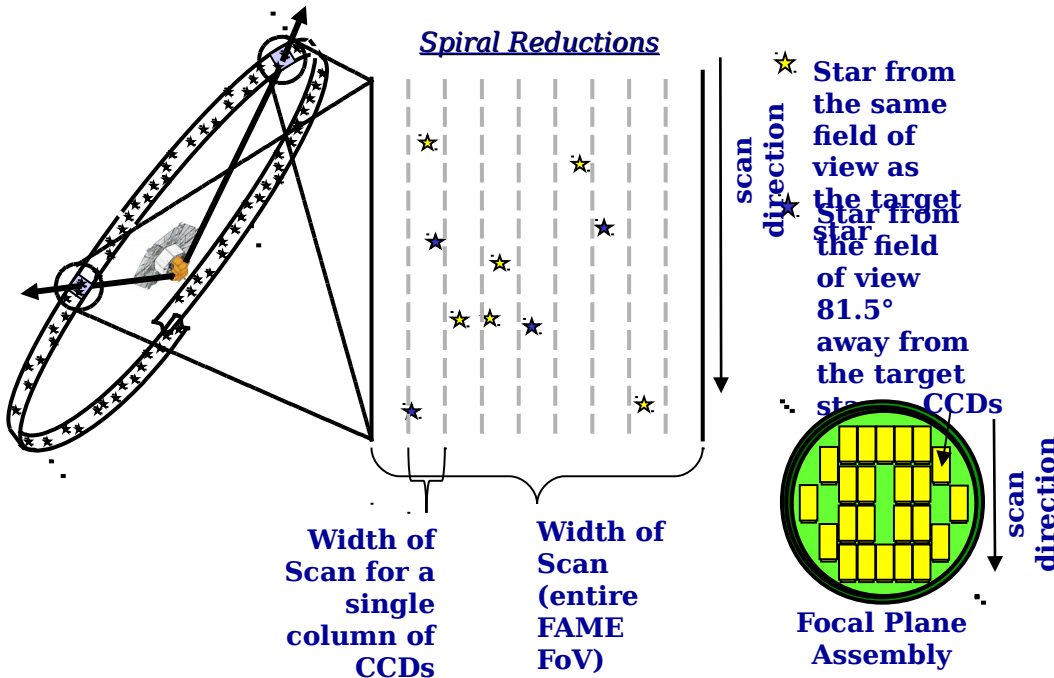
Sphere Reconstruction



FAME scan pattern - The FAME spacecraft rotates with a 40 minute period scanning the two apertures across a great circle on the sky. The 20 day precession of the spacecraft about the Sun-spacecraft line results in FAME covering the entire sky except for exclusion zones within 45° of the Sun and the anti-Sun direction every 20 days.

- ★ Use a subset of the stars to globally tie the spirals together into a sphere

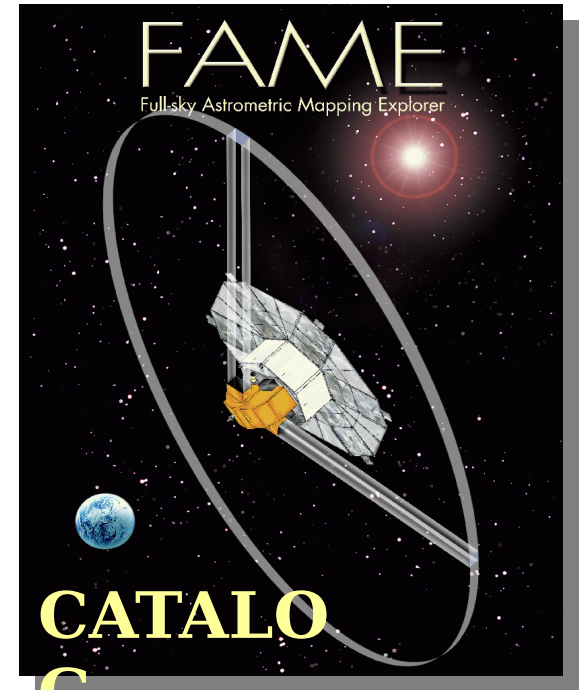
Spiral Reductions





FAME Catalog

- ◆ **Catalog available 3½ years after launch**
- ◆ **Complete catalog from the extended mission available 6 years after launch**
- ◆ **90-95% of FAME customers will want the complete catalog with nominal positions, parallaxes, proper motions, and photometry**
- ◆ **The other 5-10% will be interested in variations of a subset of the catalog over time**

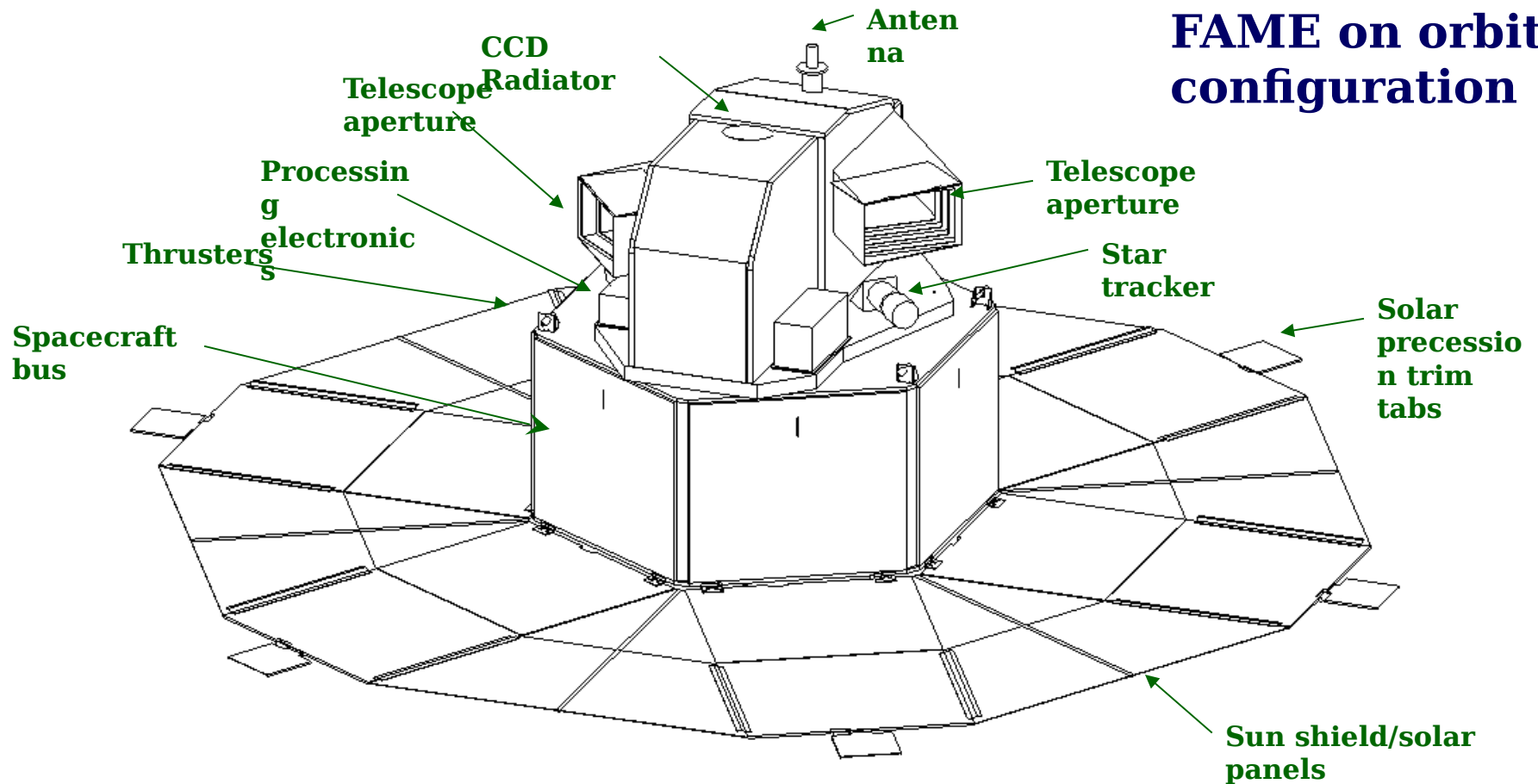


The study of fundamental properties of a large sample of stars is needed to answer many key astrophysical questions



FAME Spacecraft

**FAME on orbit
configuration**



**Spacecraft design uses component heritage from
Clementine**



FAME Schedule

**Phase A Concept
Study**

February - June 1999

Phase B

**October 2000 - June
2001**

Phase C

**July 2001 - March
2002**

Phase D

**April 2002 - June
2004**

Launch

June 2004

Phase E

**July 2004 - January
2008**

DoD Extended Mission





Most Important Science Result

FAME opens up a new dimension in stellar astrophysics

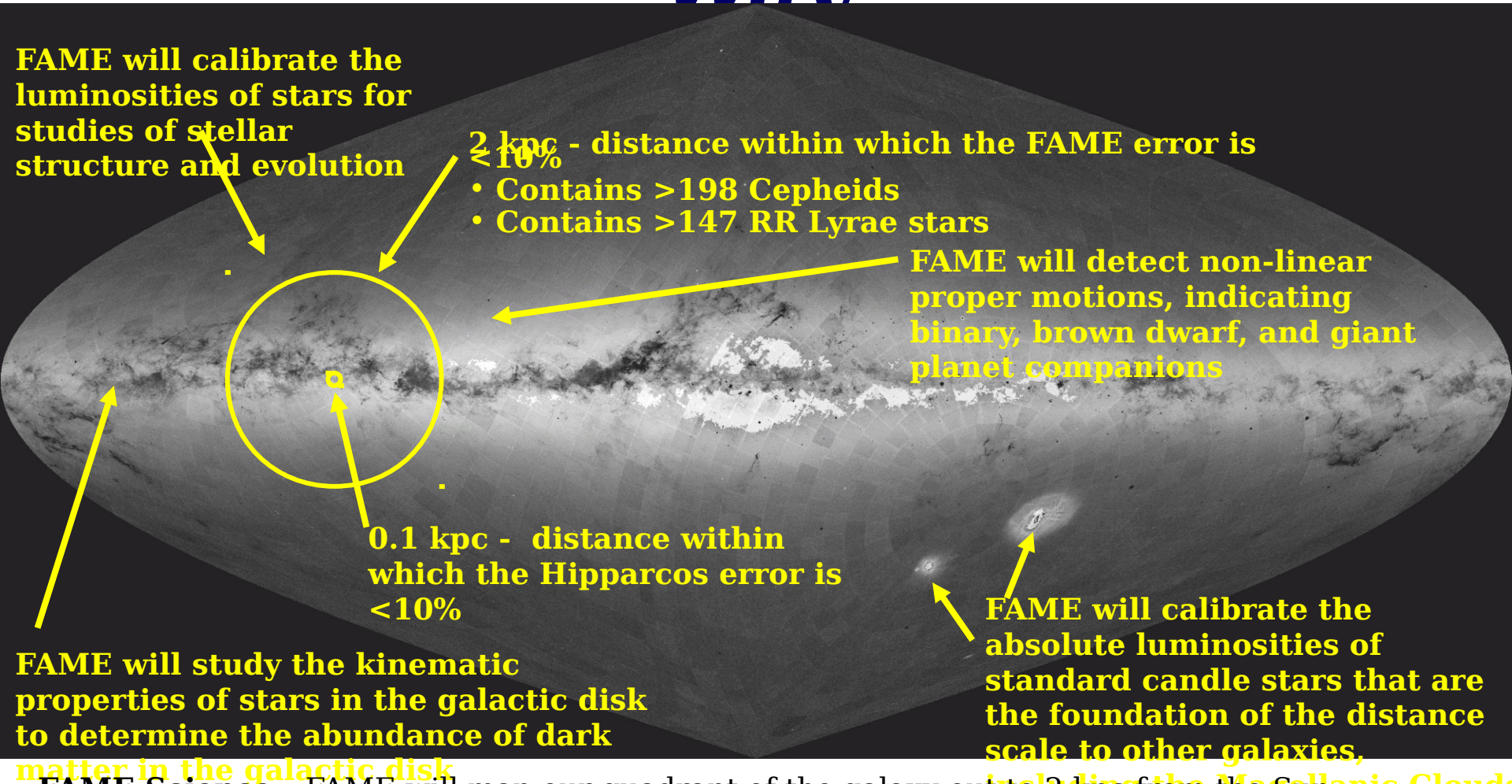
- ◆ **Stellar evolution and structure: calibration of absolute luminosities**
- ◆ **Extragalactic distance scale: determine distances to “standard candle” stars which are fundamental in defining distance scales**
- ◆ **Measure the distance to the Magellanic clouds to 2% accuracy**
- ◆ **Determine the abundance of dark matter in the galactic disk**
- ◆ **Discover brown dwarfs and giant planet companions**
- ◆ **Statistically determine the level of optical variations in solar type stars**



Most Compelling Science Driver

- Large data set sampling ALL types of stars!**
- ◆ **Occurrence of large planets for all types of stars**
- ◆ **Very large sample of stars for evolution studies by determining absolute luminosities**
 - **Open clusters**
 - **Globular clusters**
 - **Cepheids and RR Lyrae Stars**
- ◆ **“Zero point” calibration of the distance scale to 1%**

FAME Coverage of the Milky Way



FAME Science - FAME will map our quadrant of the galaxy out to 2 kpc from the Sun providing the information needed to calibrate the standard candles that define the extragalactic distance scale, calibrate the absolute luminosities of stars of all spectral types for studies of stellar structure and evolution, and detect orbital motions caused by brown dwarfs and giant planets. FAME will not only improve on the accuracies of star positions determined by Hipparcos but also expand the volume of space for which accurate positions are known by a factor of 8,000.



Precise Photometric Survey for Magnetic Cycle Variability

Expected Photometric Uncertainty (single

Magnitude	Astrometric Filter	g, r, i Filters	Hipparcos H_p
8	0.0010	0.0016	0.011
9	0.0016	0.0025	0.015
11	0.004	0.006	0.033
13	0.010	0.016	
15	0.025	0.040	

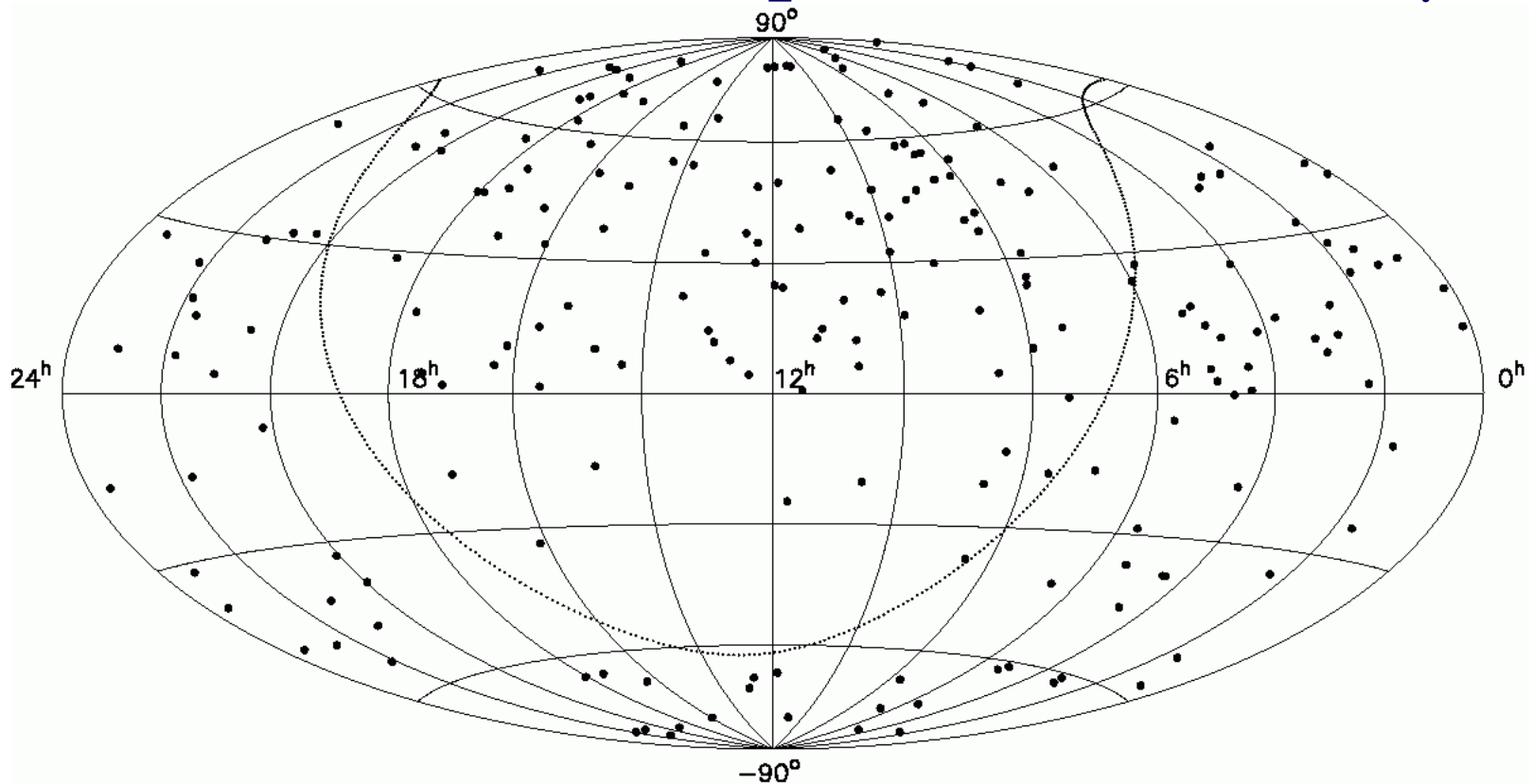
Number of stars to be surveyed by FAME (50 μ as at mag.
= 10.0)

Luminosity Class	O	Total = 500,000	B	A	F	G	K	M0
I, II, III				3700	30000	50000	20000	
V	45	130000	50000	130000	40000	9000	1170	
White Dwarf		25	10					

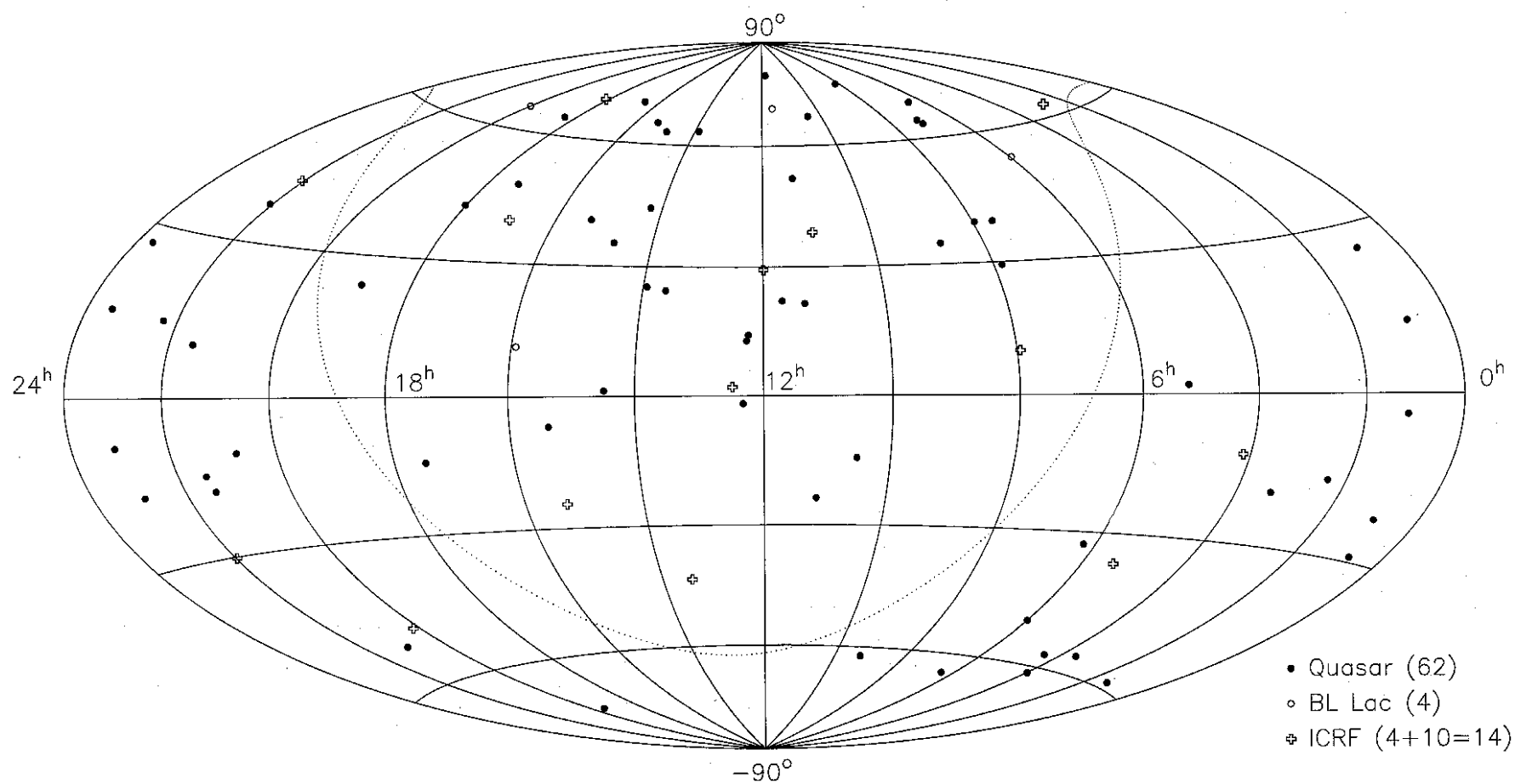


Radio Reference Frame

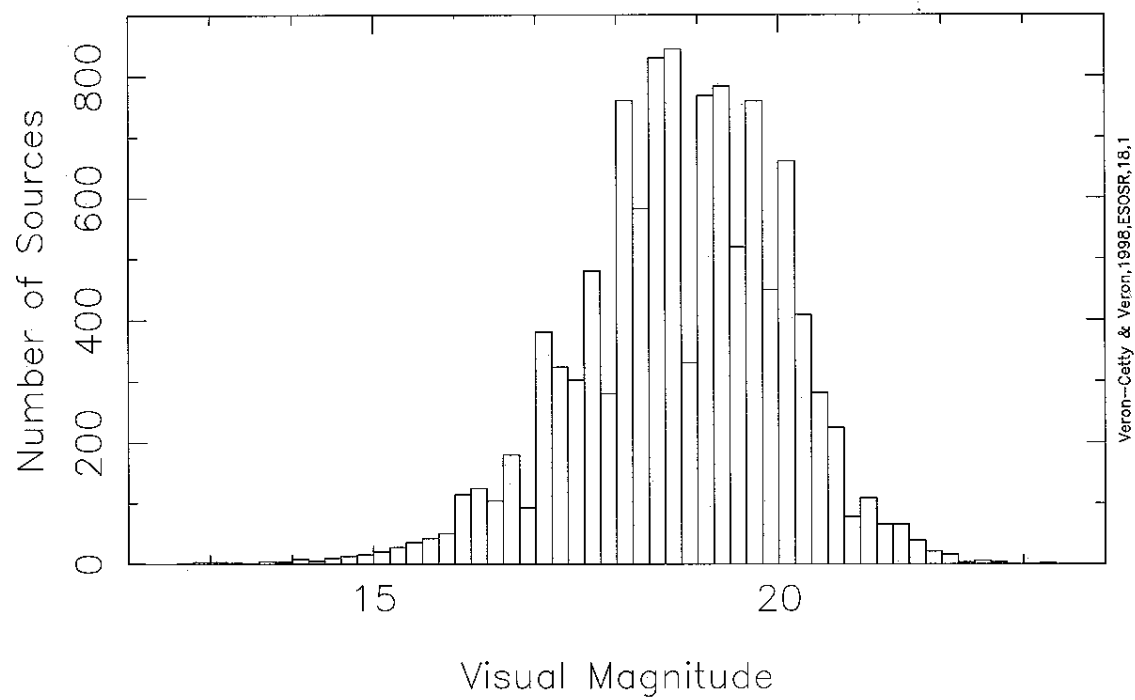
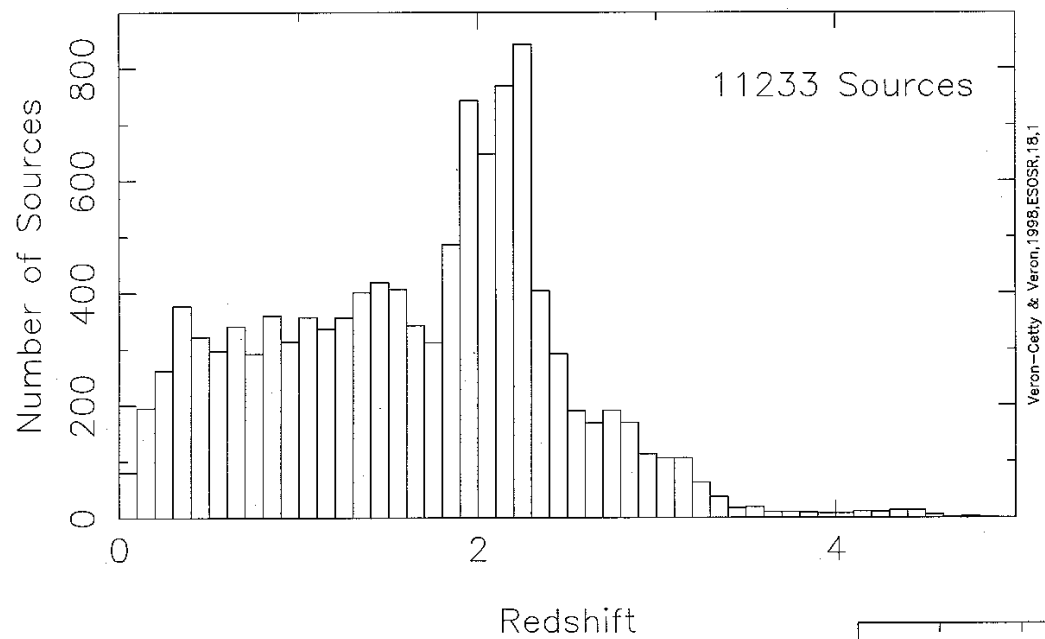
- ◆ **ICRF adopted in 1998**
- ◆ **Individual source positions to 300 μ as**



Quasars & BL Lac Objects with $M_V < 15$



Quasars and BL Lac Objects





Fame Summary with Regard to SIM

- ◆ **Launch July 2004**
- ◆ **Survey 50×10^6 stars**
- ◆ **Accuracy $50 \mu\text{as}$ @ $M_v \leq 9$**
- ◆ **Input Catalog**

**→ Precursor/Contemporary of
SIM**



Relationship to SIM Grid Stars

- ◆ **FAME can/will survey all of SIM Grid Star Candidates**
- ◆ **Reference Frame compatible or better**
 - » **$M_v \leq 10$ compatible $0.05 \mu\text{as}$**
 - » **$M_v \leq 12$ better**



Relationship to ICRF

◆ QSO/BL LAC:

- » **FAME limited to $M_v \leq 15$**
- » **SIM limited by observing time**

◆ Radio Stars

- » **FAME: All**
- » **SIM: Probably All**

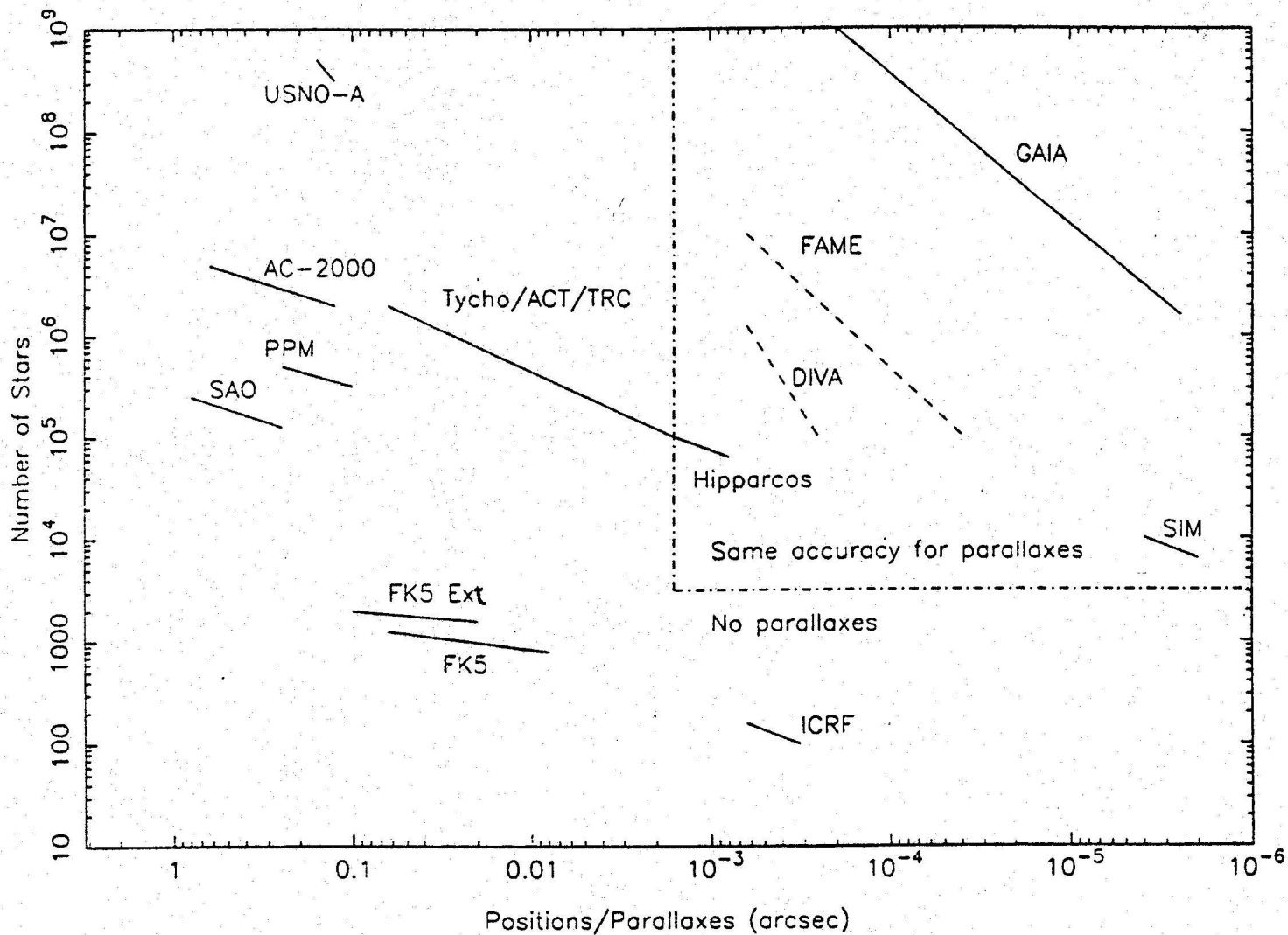
◆ Radio/Optical Frame Tie

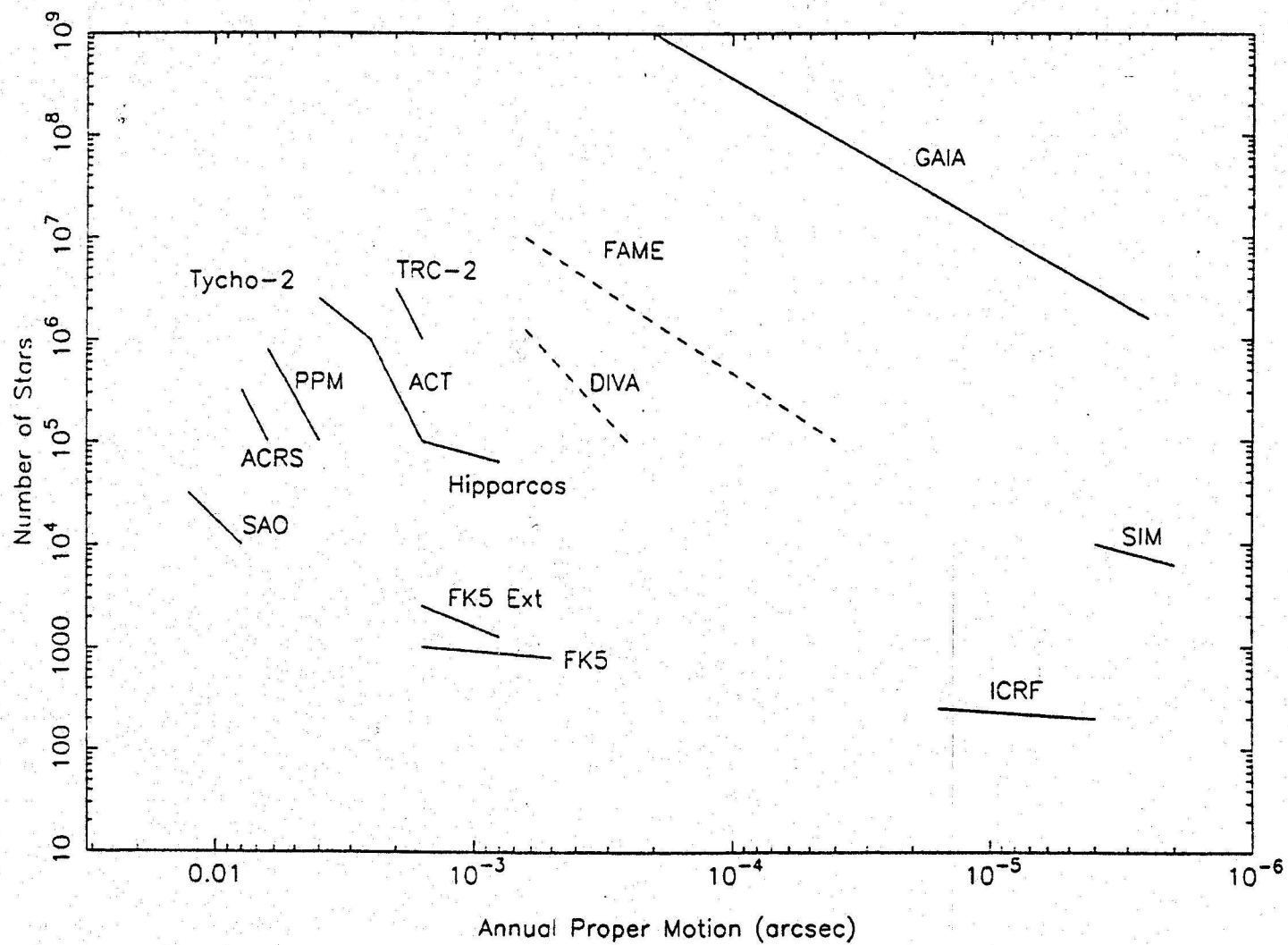
- » **Limited by radio accuracy**



Issues

- ◆ **FAME Survey not complete at SIM Launch**
 - » **50 μ as available Jun 08**
 - » **38 μ as available Jul 10**
- ◆ **FAME early results**
 - » **Can positions, proper motions and Π be obtained from one year or less of mission data?**







Conclusions

- ◆ Need close cooperation to maximize science between FAME and SIM
- ◆ Catalogs will be available:
 - FAME: 2008/2010
 - SIM: 2013
 - GAIA: 2017



The Golden Age of Astrometry

